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X-RAY PREIONIZATION FOR ELECTRIC DISCHARGE LASERS.(U)

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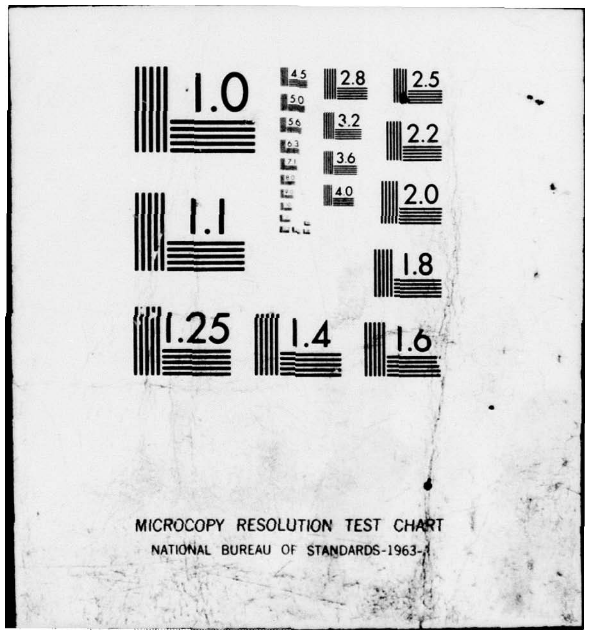
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X-ray Preionization for Electric Discharge Lasers

Final Technical Report

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6 X-ray Preionization for Electric Discharge Lasers

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Abstract

Using x-rays of 60-200 keV photon energy ($\lambda \sim 0.06$ to 0.2 Å) lambda ranges from as an ionizing radiation source in a transmission-line-driven, low-inductance discharge chamber, we have succeeded in generating spatially-homogeneous pulsed avalanche discharges of several liter volume at greater than 1 atm pressure for up to 100 nsec duration. In concurrent laser generation experiments with relatively lossy windows, we have observed high optical quality pulsed uv laser output of up to 2 J/liter from such discharges in rare gas/halogen mixtures, and ir laser output of up to 12.5 J/liter from a $He/N_2/CO_2$ mixture.

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Electrically-pumped, high pressure, large-volume gas lasers hold good promise for providing the needed coherent radiation sources in a number of applications involving very high peak and average powers in a repetitively pulsed mode of operation (e.g., laser driven fusion, industrial-scale photochemistry, isotope separation, etc.). Advantages of such lasers include convenient pumping energy source, high generation efficiency, broad wavelength coverage, and relative invulnerability to self destruction. At present, there are three known methods for electrical pumping of high pressure gas lasers: (i) direct e-beam (high energy electron beam) pumping,[1] (ii) e-beam sustained discharge,[2] and (iii) e-beam or uv preionized avalanche/self-sustained discharges.[3] In all three methods, scaling to large laser volumes will ultimately be limited by the mass penetration depth of the electron beam or of the other ionizing radiation source employed.

The characteristic length scale corresponding to one e-fold attenuation of current density for a 300 keV electron beam in a typical rare gas/halogen or N_2/CO_2 laser mixture at room temperature and 1 atm total pressure is only about 20 cm.[4] Accordingly, homogeneous pumping of the laser gas of mass thickness much greater than 0.2 meter-atmosphere at room temperature would require relativistic electron beams of very high energy. The effective range for uv preionization in molecular lasers has also been found experimentally to be of the order of 0.1 m-atm.[5] On the other hand, the mass thickness for an e-fold intensity attenuation of x-rays at 200 keV photon energy is about 5, 13, 50 and 110 m-atm in pure Xe, Kr, A and Ne, respectively, at room temperature.[6] Thus, if x-rays are used as the ionizing agent in place of high energy electrons or uv photons in methods (ii) and (iii), the mass thickness of the laser gas mixtures amenable to homogeneous pumping can be greatly increased. In fact, since the mass penetration depths for x-rays are so great even at photon energies down to a few tens of keV, one may expect that in x-ray sustained and x-ray preionized gas discharge lasers, the maximum practical size of the laser will more likely be limited by E/n (electric field/gas density) and subsequent discharge homogeneity considerations than by the penetration depth of the x-rays.

High pressure and/or high repetition rate operations of e-beam pumped and e-beam sustained gas lasers are also severely limited by the mechanical strength and heat transfer properties of the thin foil window necessary for transmission of the e-beam from its high vacuum source to its high pressure target.[7] The much greater mass penetration thickness of x-rays (by a factor of about 10^3 in low-Z materials) will make the problem of providing cooled, shadowless, high pressure windows relatively easy.

The method and principle for generating x-rays are well known. When a high energy e-beam impinges on a high-Z material of appropriate thickness, a significant fraction of the e-beam energy can be converted into electromagnetic radiation. The major process is free-free emission (Bremsstrahlung), which produces a continuous spectrum with peak intensity at about 1.5 times the minimum wavelength,[8] $\lambda_{min} = hc/E_b$, where h is Planck's constant, c is the velocity of light in vacuum, and E_b is the initial energy of the beam electron. The x-ray production efficiency is given approximately by the formula,[9] $\eta = E_b Z/700$, where E_b is in units of MeV and Z is the atomic number of the target material. Thus, a 300 keV e-beam impinging on a tungsten target (Z = 74) will have an x-ray production efficiency of about 3%, a spectral peak of 200 keV, and a mean photon energy of 150 keV.[8]

Since the x-ray production efficiency is typically low, externally sustained discharge lasers relying on the x-ray induced ionization for control of the current distribution are viable only when the discharge enhancement ratio[10] is very high or when effective pumping of the upper laser level can be done at very low electron mole fractions as in the case of most ir lasers such as CO_2 and HF. For homogeneous avalanche/self-sustained discharge lasers, however, the low x-ray production efficiency is not an important consideration because the required preionization density can be very low ($\sim 10^6 - 10^8$ electrons/cm^3).[11]

For x-rays with photon energies below a few hundred keV propagating in a gas mixture, the primary absorption process is photoionization. This process results in the production of positive ions and high energy photoelectrons which subsequently undergo cascade ionization until their kinetic energies fall below the molecular ionization potential. The average energy required to produce an electron-ion pair is about 30 eV in most gases,[12] so that an absorbed 200 keV x-ray photon will generate about 7,000 ion pairs. Thus, except for the great difference in mass penetration depth, the behavior of x-rays as a source of volume ionization is actually very similar to that of the high energy e-beam.

In order to test the viability of using x-rays as a high intensity preionization source, modifications were made to an existing[10] large area (10 cm × 110 cm) cold cathod electron gun. A 0.013 mm thick tantalum target foil was placed inside the e-gun vacuum chamber thus converting the system into a large area x-ray source. Measurement of the pulsed x-ray intensity were made by using pure argon at 1 atm pressure as an absorber and monitoring the total current collected by the electrodes of the laser chamber under the influence of a weak constant electric field. In pure argon, the loss rate of ion pairs is expected to be governed primarily by the dimer ion formation and dissociative recombination processes,

$$Ar^+ + 2Ar \xrightarrow{k_1} Ar_2^+ + Ar \qquad (1)$$

$$e + Ar_2^+ \xrightarrow{k_2} Ar^* + Ar \qquad (2)$$

with rate constants $k_1 \cong 3 \times 10^{-31}$ cm^6/sec and $k_2 \cong 2 \times 10^{-6}$ cm^3/sec, respectively.[13, 14] It can be shown that if the volume ionization source strength S_o is a step-function switched on at time $t = 0$, the transient electron number density for $t > 0$ will be approximately [assuming $S_o \ll (2k_1 n_{Ar}^2)^2/k_2$],

$$n_e(t) = n_{es} \tanh (k_2 n_{es} t) \qquad (3)$$

where

$$n_{es} = [(S_o/k_2) + (S_o/2k_1 n_{Ar}^2)^2]^{1/2} \qquad (4)$$

is the quasi steady state value of $n_e(t)$ at late times. If S_o is maintained only for a limited period Δt and then turned off, one would expect n_e to rise in accordance with Eq. (3) only up to $t = \Delta t$ and then decay at a rate governed by processes (1) and (2). The time history of n_e observed in our x-ray absorption chamber[15] is in good agreement with this theoretical expectation as illustrated in Fig. 1a. In this example, the e-gun voltage and current density were $V_b = 200$ kV and $j_b = 8$ A/cm^2, respectively, and the pulse duration Δt was approximately 1.5 μsec. It is seen that the rising part of $n_e(t)$ can be fitted quite closely by Eq. (3) if one lets $n_{es} = 6.7 \times 10^{11}$ cm^{-3}. From this value of n_{es}, one can deduce $S_o = 9 \times 10^{17}$ ion pairs/cm^3-sec from Eq. (4). The source strength so deduced is found to be consistent with the value of S_o that can be calculated independently from the e-gun power flux on the target foil, $V_b j_b = 1.6 \times 10^6$ watts/cm^2, the x-ray production efficiency $\eta \cong 0.02$; the x-ray absorption coefficient for argon at 1 atm pressure and at 100 keV average photon energy, $\mu = 4 \times 10^{-4}$ cm^{-1}; the average energy to produce one ion pair $\epsilon_p \cong 30$ eV $\cong 3.2 \times 10^{-18}$ J; and an estimated beam utilization factor $f \cong 0.25$ which also takes into account transmission and scattering losses; such that $S_o = V_b j_b \eta f \mu / \epsilon_p \cong 10^{18}$ ion pairs/cm^3-sec.

To see if x-ray ionization was suitable as a preionization technique for pulsed discharge lasers, a new multi-liter volume fast discharge laser system was recently constructed in our laboratory (Fig. 2). This laser was designed primarily for use with the rare gas-halogen systems and so is of a very low inductance design. The estimated inductance of the new laser chamber, including high voltage feed-throughs, is less than 4 nH. The laser is connected directly to a water dielectric double-parallel-plate transmission line by a multi-arc-channel rail gap. The circuit is so designed that when the x-ray source is triggered on, the laser PFN is automatically activated within a preset time delay. The chamber is made of stainless steel, aluminum, teflon and Kynar (polyvinylidene fluoride) and is therefore totally halogen compatible. The maximum pressure capability of the laser is 6 atm and the electrode spacing can be varied between 1 and 9 cm giving a maximum usable discharge volume of about 6 liters. The laser PFN has a nominal line impedance of 0.5 ohm and has a variable electrical length (two-way transit time). However, during the studies described here, an electrical length of 100 nsec was used exclusively. The line is switched by a rail spark gap[16] that operates in 100 or more simultaneous arc channels allowing the voltage rise time on the laser chamber electrodes to be shorter than 10 nsec. (See Fig. 1b.)

The first test of our x-ray preionization technique was made in the CO_2 ir laser. Using a mixture of $He:N_2:CO_2 = 3:1:1$ at 1 atm total pressure and a charging voltage of 75 kV on the PFN, a uniform glow discharge of about 3.5 liter volume resulted. The electrode spacing was 5 cm. When an optical cavity consisting of a total and a 90% reflector was placed around the discharge, an output of 12.5 J/liter was extracted. The input energy density was $\sim$ 106 J/liter, implying a laser efficiency of $\sim$12%.

Our first uv laser generation experiments using x-ray preionized pulsed avalanche discharges with very large ($> 10^3$) current multiplication were tried with the electrodes set at a relatively close spacing of 3 cm. Using rare gas mixtures containing typically 0.2% halogen, a PFN charging voltage of 71 kV, and a maximum gas pressure of 2.4 atm, we obtained spatially uniform discharges of about 1 liter volume for a full 100 nsec with no sign of arcing. This is illustrated in Figs. 3a and 3c which show a

Polaroid photograph of the homogeneous plasma luminosity from the x-ray preionized discharge and the corresponding uniform uv laser burn pattern on a piece of developed Polaroid film mounted 1 m away from the output mirror. The laser pulse energy output was typically 2.0 J for XeCl, 1.4 J for KrF, and 0.25 J for XeF.[17] The laser energy was measured using a Gen-Tech ED-500 pyroelectric detector and the output pulse shape was monitored using a calibrated ITT biplanar photo-diode in conjunction with a Tek 519 oscilloscope. A typical voltage waveform across the discharge electrodes and the resulting laser output pulse for KrF is shown in Figs. 1b and 1c. It is interesting to note that after the initial avalanche and current multiplication phase, the discharge voltage does not collapse to zero but settles along a quasi-steady plateau, indicating that the discharge was running in a stable self-sustained mode for the remaining duration of the electrical pulse.

In more recent experiments in which the discharge gap was changed to a spacing of 6 cm, we have succeeded in extending the homogeneous discharge volume to about 2.5 liter at 1 atm pressure. Preliminary laser generation experiments indicate that under appropriate conditions, it should be possible to extract 2 J/liter from this entire volume at an efficiency of ~ 1.4% based on the energy storage in the PFN. If this trend continues, and the stability of the self-sustained discharge can be maintained over periods much longer than 100 nsec, our present experiments indicate that uv excimer laser generation at pulse energy much greater than 2 J/liter and efficiency significantly higher than 1.4% should be possible for x-ray preionized, high-pressure, large volume discharges.

FOOTNOTES AND REFERENCES

[*]Work supported jointly by the Office of Naval Research under Contract N00014-77-C-0692 and by the Defense Advanced Research Projects Agency under Contract N00014-76-C-0116.

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[15] Obtained from dividing the total ionization current by the product of the effective collecting area of the anode, the electronic charge, and the electron drift velocity in argon at the collecting E/n_{Ar} employed.

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[17] The XeCl laser energy was extracted by sealed intracavity mirrors mounted directly at the ends of the laser chamber. Extraction of the KrF and XeF laser energies, on the other hand, was done by mounting the cavity mirrors external to a pair of badly etched (and hence lossy) quartz windows at the ends of the laser chamber for containment of the corrosive F_2 gas in the $He/Kr/F_2$ and $He/Xe/F_2$ mixtures. This may account for the relatively low KrF and XeF laser outputs in comparison with that of the XeCl laser.

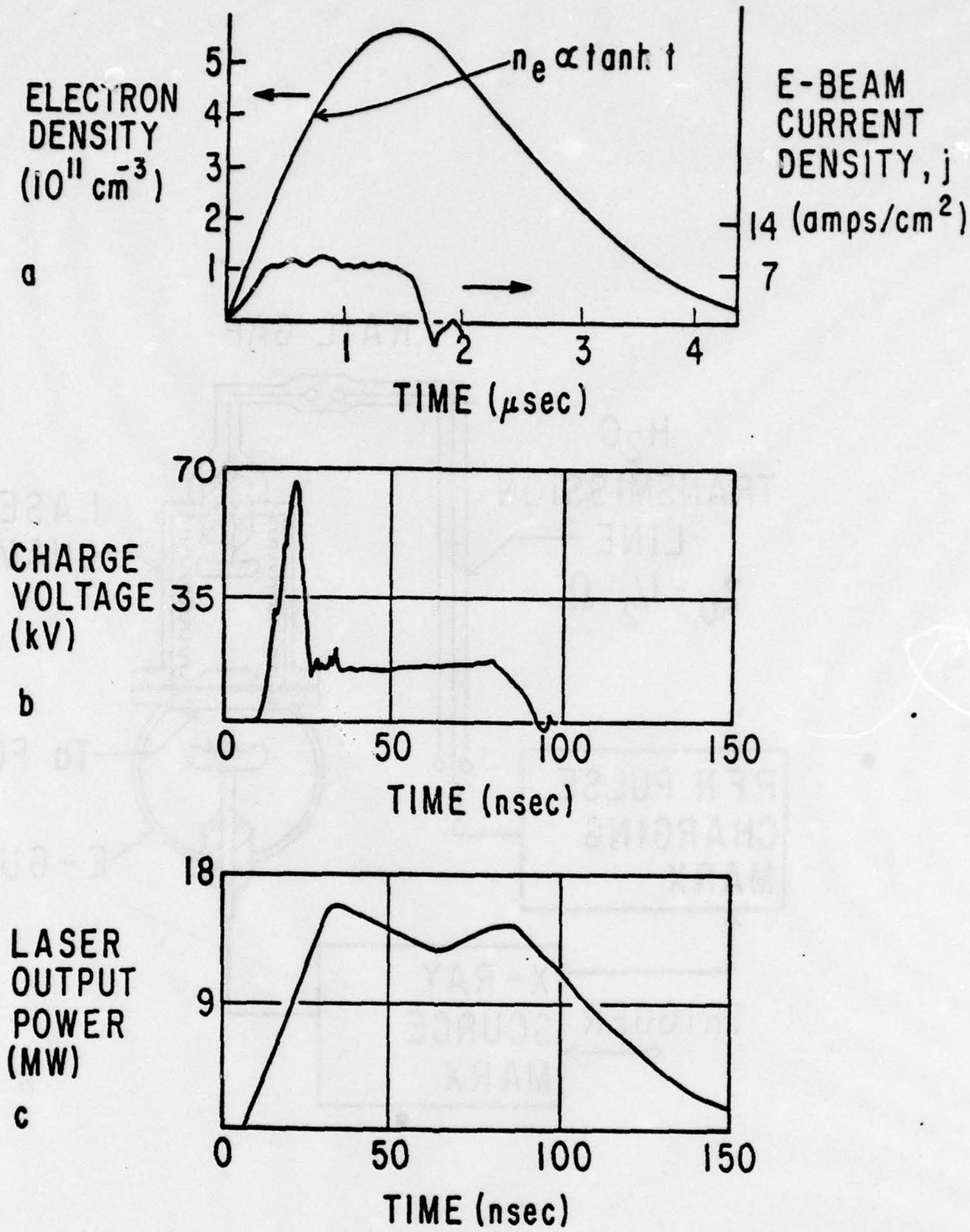

Fig. 1 Typical time histories reproduced from oscillographic records showing: (a) x-ray induced electron number density observed in pure argon, and the corresponding e-beam current density on foil target which generated the x-ray pulse; (b) voltage across the electrodes at 3 cm spacing during an x-ray preionized discharge in the new laser chamber containing a He:Kr:F_2 = 958:40:2 mixture at 2 atm total pressure; and (c) KrF laser output observed under the same discharge conditions as in (b). Note persistence of KrF laser output after termination of the electrical pulse, which was observed only in the KrF discharge. In XeCl, the laser output was observed to terminate simultaneously with the electrical pulse like a square-wave.

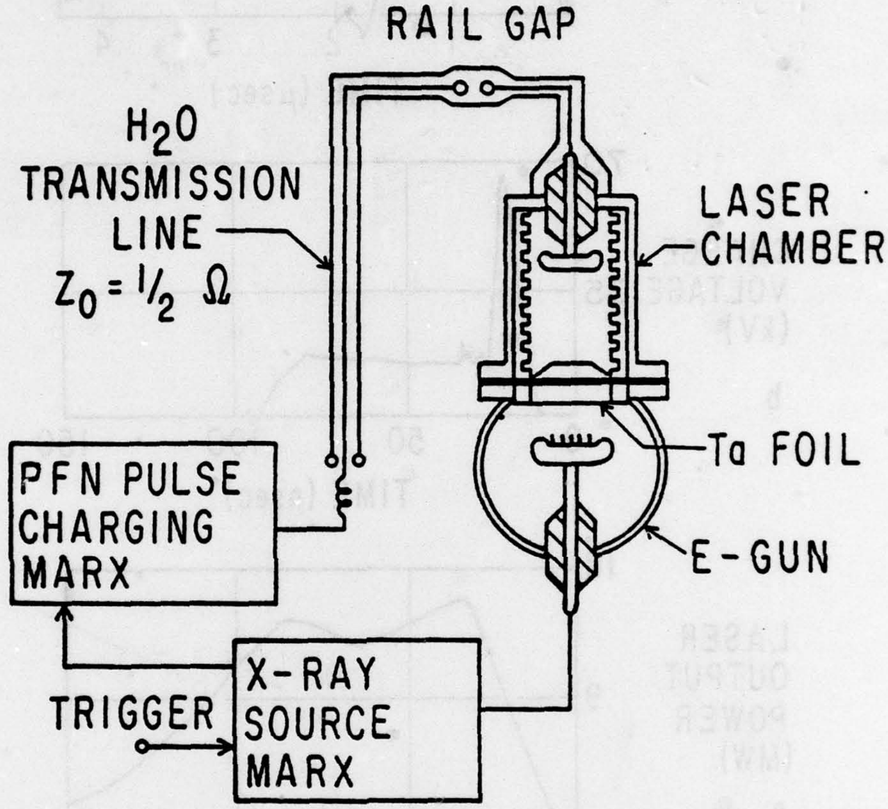

Fig. 2 Schematic diagram showing cross-sectional view of the new laser chamber and other experimental arrangement.

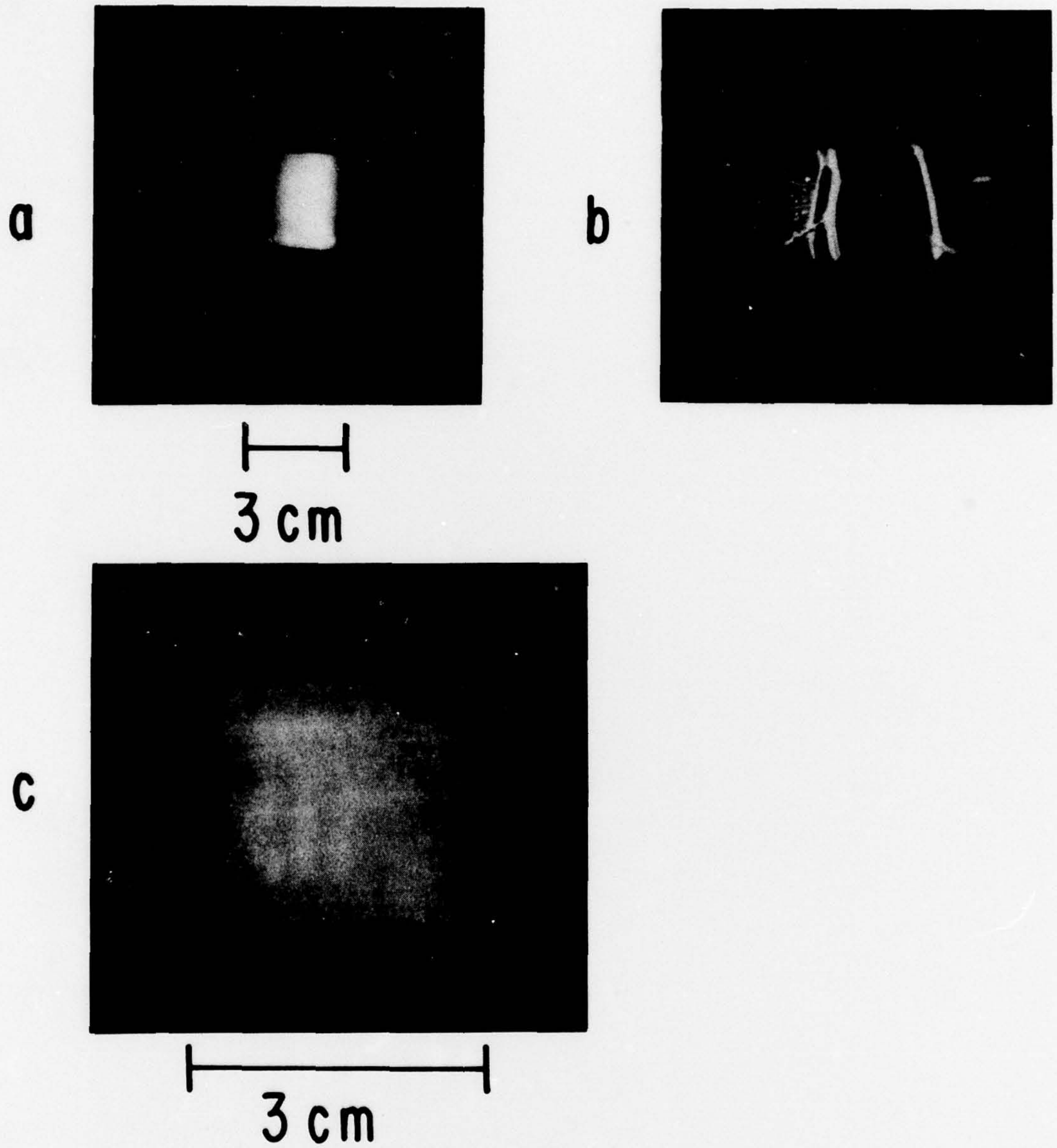

Fig. 3 Top row: Polaroid photographs from open-shutter camera looking directly into the laser chamber through one of the quartz end windows during a discharge in rare gas/halogen mixture showing (a) homogeneous discharge in x-ray preionization, and (b) inhomogeneous discharge in the absence of x-ray preionization. Bottom picture: uv burn pattern on Polaroid film target from the output beam of a single pulse, x-ray preionized, rare gas halide excimer laser discharge.